Supersymmetry and the Matter-Antimatter Asymmetry

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Standard Model

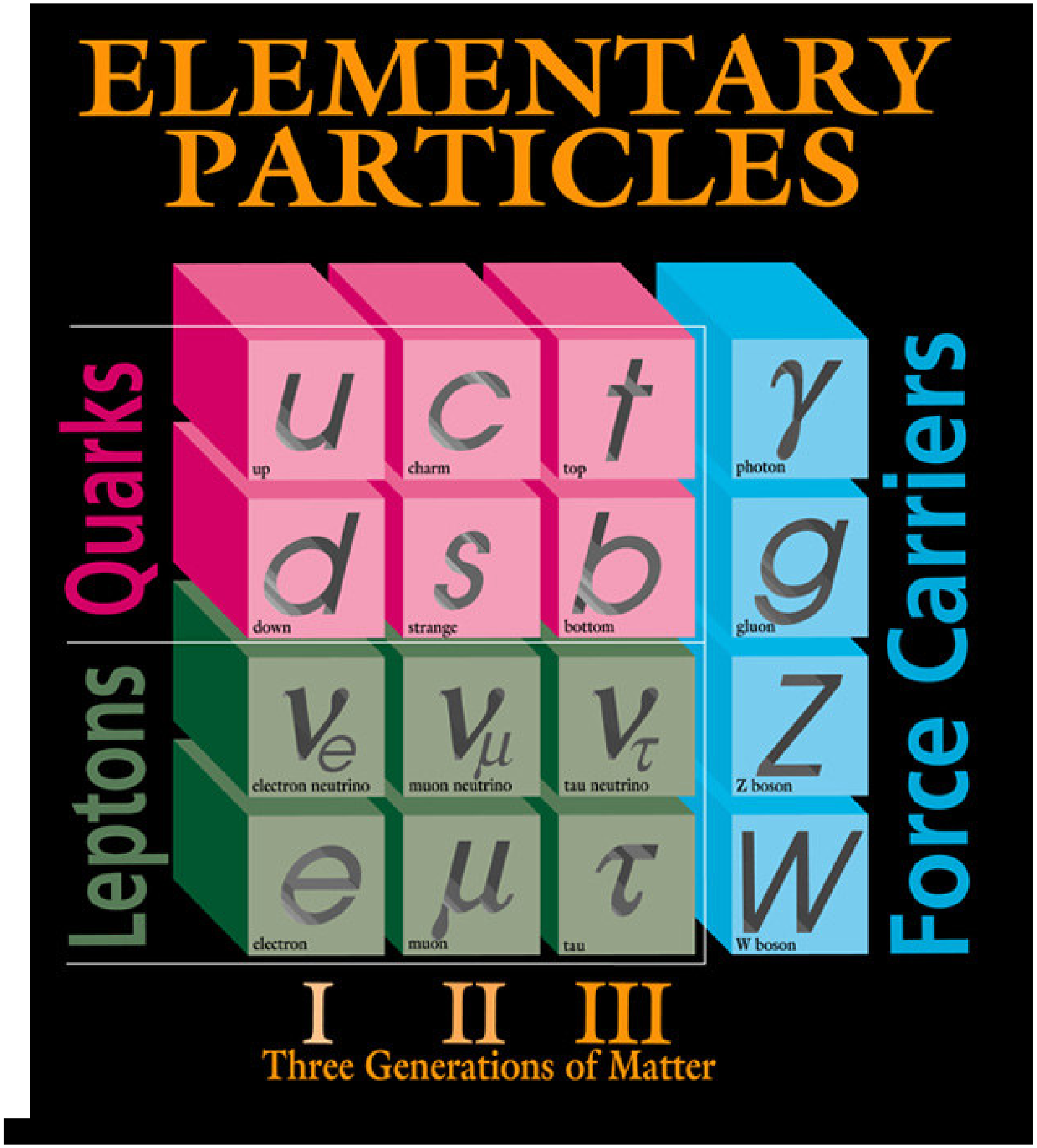
- Gauge Theory Based on the group

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

- All particle interactions of the three families of quarks, charged leptons and neutrinos well described by the Standard Model (SM)

- Excellent description of all experimental observables

- Includes heavy particles, like the top quark and the weak gauge bosons, as well as the almost massless neutrinos.


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u up
c charm
t top
d down
s strange
b bottom
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
e electron
μ muon
τ tau
γ photon
g gluon
Z Z boson
W W boson
I II III
Three Generations of Matter

Particles and Forces

Photons mediate standard electromagnetic interactions.
Quarks carry fractional charges.

Quarks form baryons (nucleons) and interact via strong forces mediated by gluons. They are confined inside hadrons.

Both quarks and leptons interact with the short range weak forces mediated by the heavy W and Z gauge bosons, with masses of order 100 GeV (1 GeV = Proton Mass).
Responsible for beta decay

$$\mathrm{n} \Rightarrow \mathrm{p} + \mathrm{e} + \bar{\nu}$$

Open questions in the Standard Model

- Source of Mass of fundamental particles.
- Origin of the observed asymmetry between particles and antiparticles (Baryon Asymmetry).
- Nature of the Dark Matter, contributing to most of the matter energy of the Universe.
- Quantum Gravity and Unified Interactions.

Origin of Mass

Origin of Mass of Fundamental Particles

- Although most of the observable mass in the Universe comes from stong interacting bound states (nucleons), the masses of fundamental particles are a mystery.

- In the Standard Model, masses occur due to the spontaneous breakdown of the gauge symmetry.

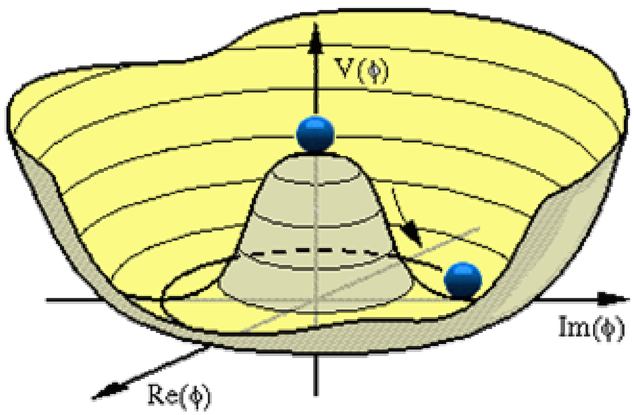
- SU(3) QCD interactions break the $SU(2)_L$ x U(1) symmetry,

$$< \bar{\Psi}_L \ \Psi_R > = \Lambda_{QCD}$$

- The Λ_{QCD} scale, of order of 300 MeV, is too small to explain the gauge boson and the top-quark masses, of order 100 GeV .

- New mechanism necessary.

The Higgs Mechanism



Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

$$M_{W,Z} = g_{W,Z}\, v$$

$$m_{top} = h_{top}\, v$$

$$m_H^2 = \lambda\, v^2$$

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy

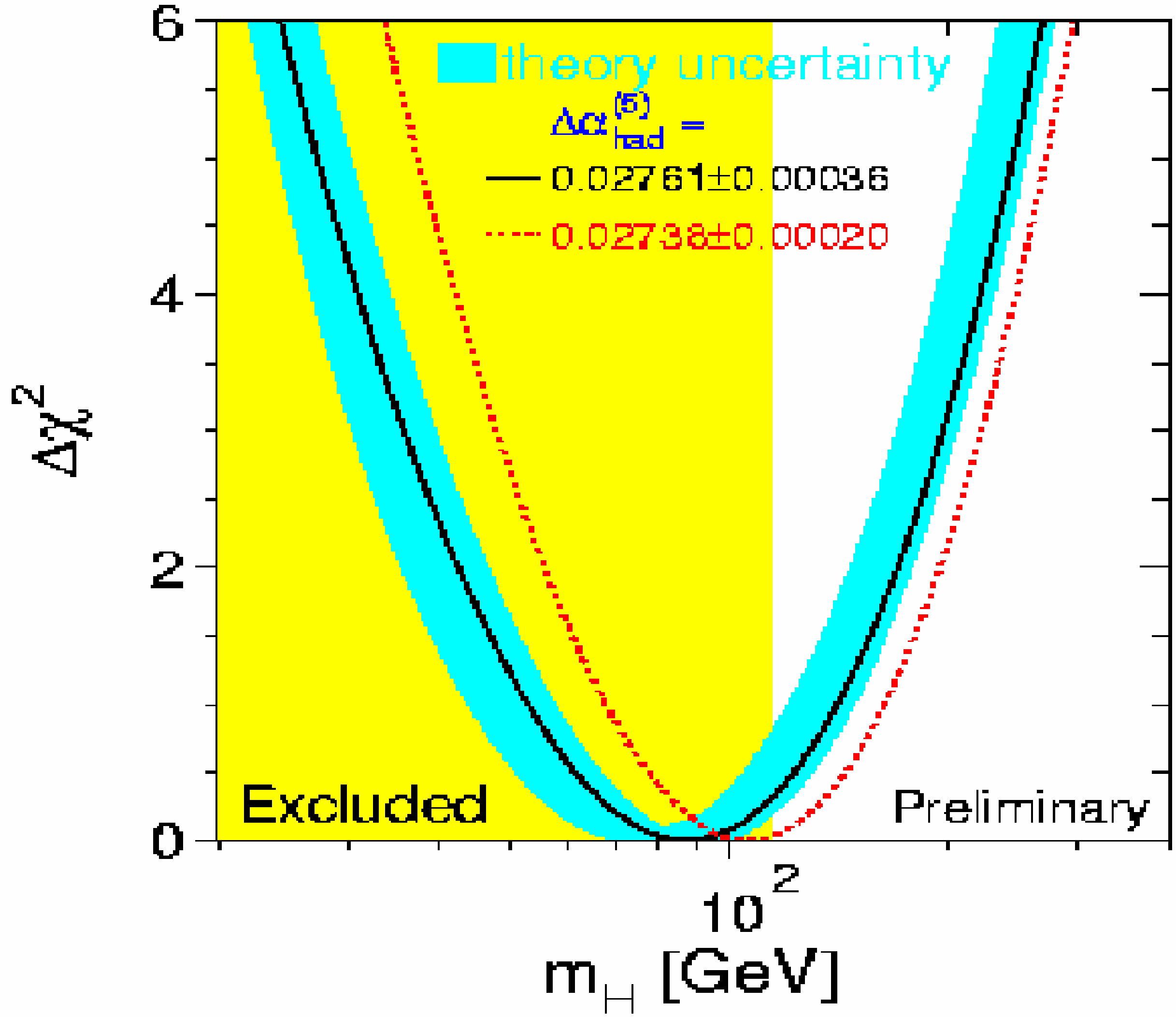
$\Downarrow$

Spontaneous Breakdown of the symmetry $\langle \phi \rangle = v$

$\Downarrow$

Vacuum becomes a source of energy = a source of mass

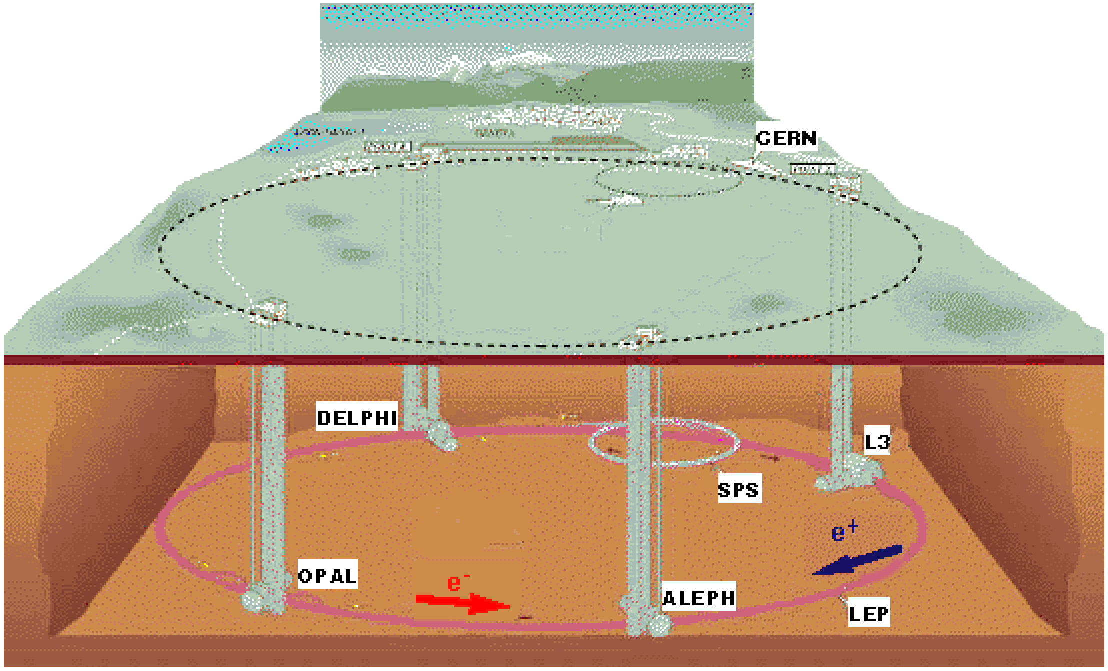
Constraints on the Higgs mass originating from its quantum effects on observables measured at different colliders.



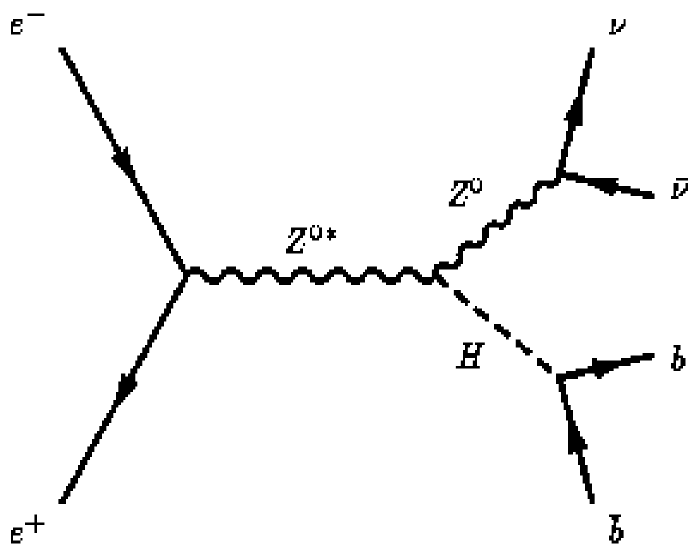
Higgs Boson Masses smaller than 200 GeV preferred.

The Search for the Higgs Boson

- At The Large Electron Positron Collider - LEP



If the Higgs Boson is created , it will decay rapidly into other particles



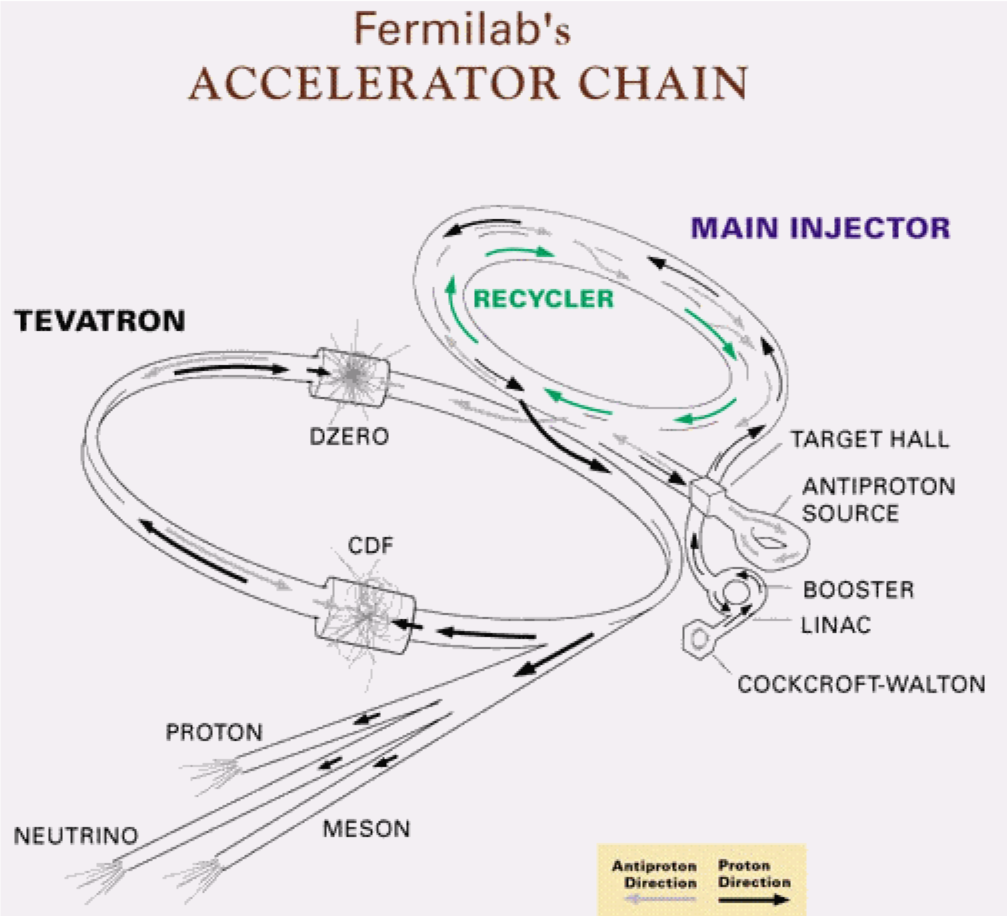
One detects the decay products of the Higgs and the Z bosons

LEP Run is over

- **No Higgs seen with a mass below 114 GeV**
- **But, tantalizing hint of a Higgs with mass about 115 -- 116 GeV (just at the edge of LEP reach)**

Next chance to reveal mechanism that can explain the origin of mass in nature → at Fermilab!

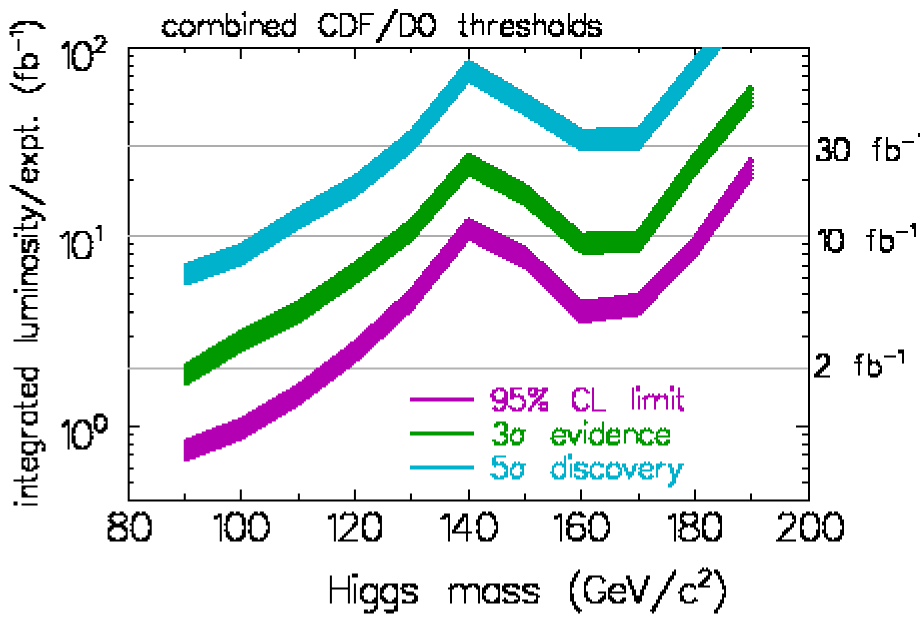
The Tevatron Run 2



Protons and antiprotons (quark and antiquark or two gluons) collide, and if the collision is energetic enough, shower of particles will be produced

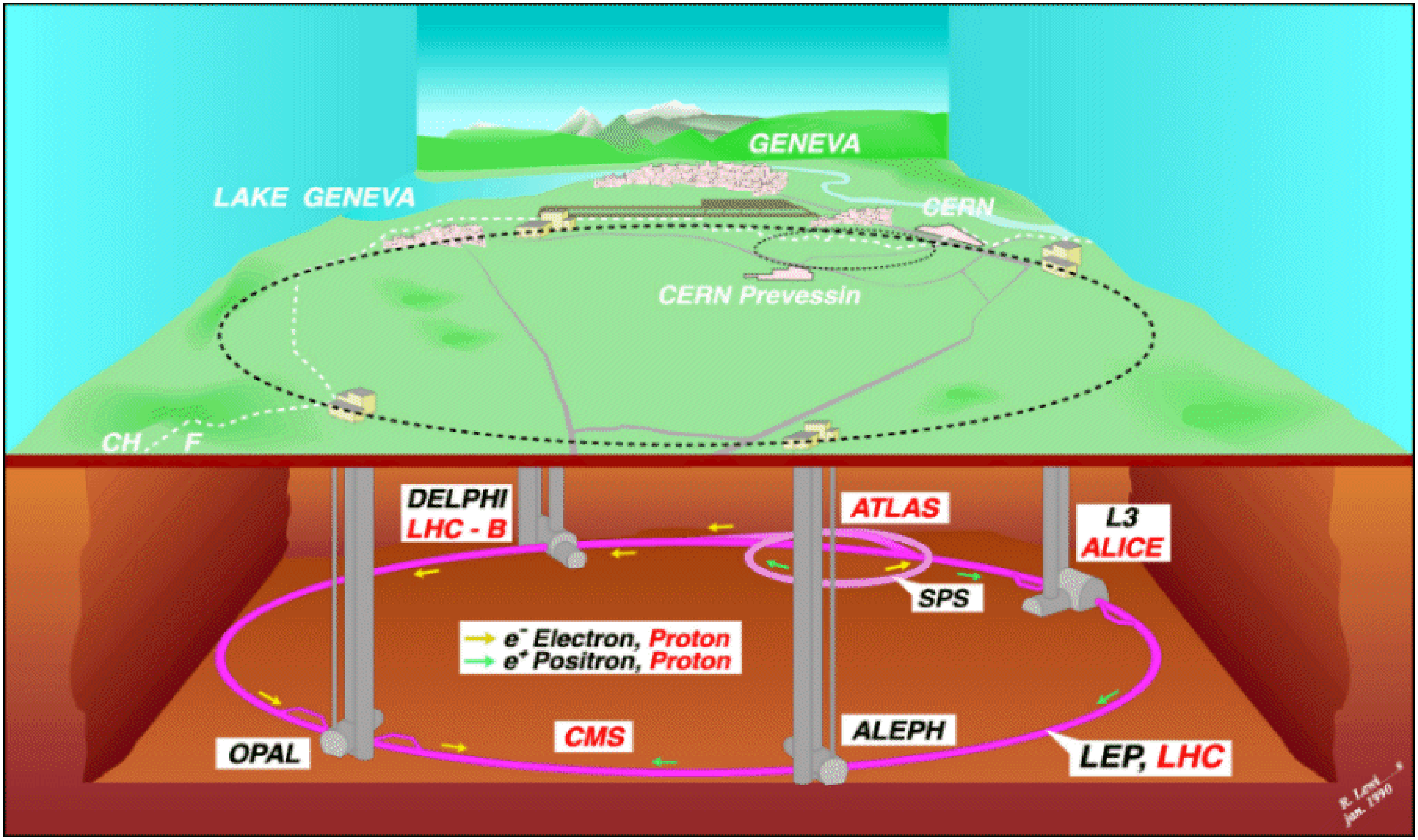
With the projected integrated luminosity by the start of the LHC, the Tevatron collider experiments can probe the presence of a Higgs boson with a mass up to about 125 GeV.

But it will not be easy



Good performance of the accelerator and detectors (high luminosity) is essential

At the LHC at CERN, Higgs boson masses in all the allowed theoretical range (up to 1 TeV) can be probed.



Origin of the Baryon Asymmetry

Lepton and Baryon Number

- Marriage of relativity and quantum mechanics: Antiparticles.

- Each particle in nature has an antiparticle of opposite charge. The antiparticle of the electron e^-, is the positron e^+.

- Why doesn't the proton decay

$$\mathrm{P}^+ \to \mathrm{e}^+\gamma \quad (\pi^0, K^0)$$

- In the SM, proton is stable due to the preservation of baryon number

Proton Stability

- Baryon number B carried by quarks, with baryon number 1/3. Proton and Neutron carry B = 1.
- Charged Leptons (electron, muon, tau) and Neutrinos carry lepton number L = 1.
- A conserved quantum number cannot change in the decay of a particle. B, L and charge are conserved.
- Stability of Proton: Lightest Baryon.
- Stability of the electron: Lightest charged particle.

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is composed of matter.
- Anti-matter is only seen in cosmic rays and particle physics accelerators
- The rate observed in cosmic rays consistent with secondary emission of antiprotons

$$\frac{n_{\bar{p}}}{n_p} \approx 10^{-4}$$

Baryon Abundance

- Information on the baryon abundance comes from two main sources:
- Abundance of primordial elements. When combined with Big Bang Nucleosynthesis tell us

$$\eta = \frac{n_B}{n_\gamma} \quad , \qquad n_\gamma = \frac{421}{cm^3}$$

- CMBR, tell us ratio

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B , \qquad \rho_c \approx 10^{-5} h^2 \frac{GeV}{cm^3}$$

- There is a simple relation between these two quantities

$$\eta = 2.68 \ 10^{-8} \Omega_B h^2$$

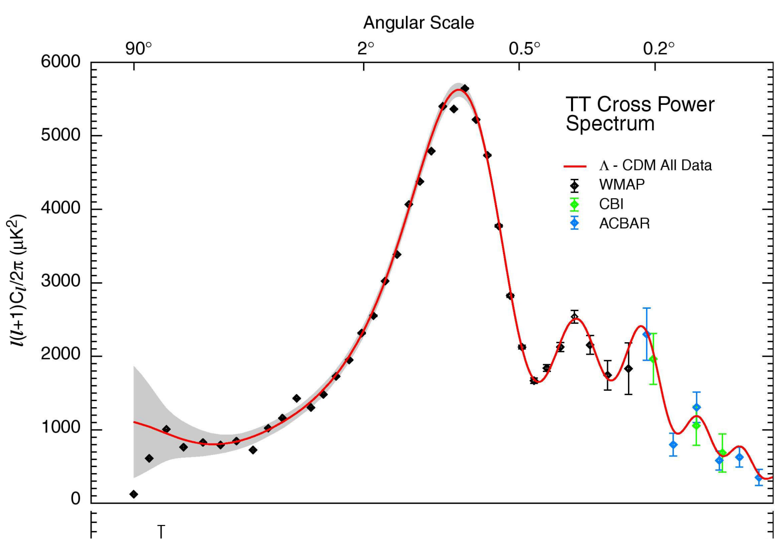
Cosmic Microwave Background
WMAP

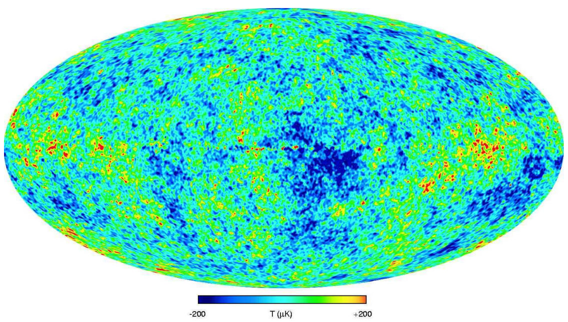
h=0.71±0.04

$\Omega_M h^2$=0.135±0.009

$\Omega_B h^2$=0.0224±0.0009

Ω_{tot}=1.02±0.02





Baryon-Antibaryon asymmetry

- Baryon Number abundance is only a tiny fraction of other relativistic species

$$\frac{n_B}{n_\gamma} \approx 6\ 10^{-10}$$

- But in early universe baryons, antibaryons and photons were equally abundant. What explains the above ratio ?

- Explanation: Baryons and Antibaryons annihilated very efficiently. No net baryon number if B would be conserved at all times.

- What generated the small observed baryon-antibaryon asymmetry ?

Generation of Baryon Asymmetry

Three conditions, first defined by Sakharov

- Non-conservation of Baryon Number
- C and CP Violation (Violation of symmetry of interactions under interchange of particle by antiparticles)

Otherwise, number of baryons would equal number of antibaryons

- Non-equilibrium processes (Rate of increase of B larger than the one of decrease of B)

All three requirements fulfilled in the SM.

Baryon Number Violation in the Standard Model:

Baryon Number conserved at the classical level but violated at the quantum level: Anomaly

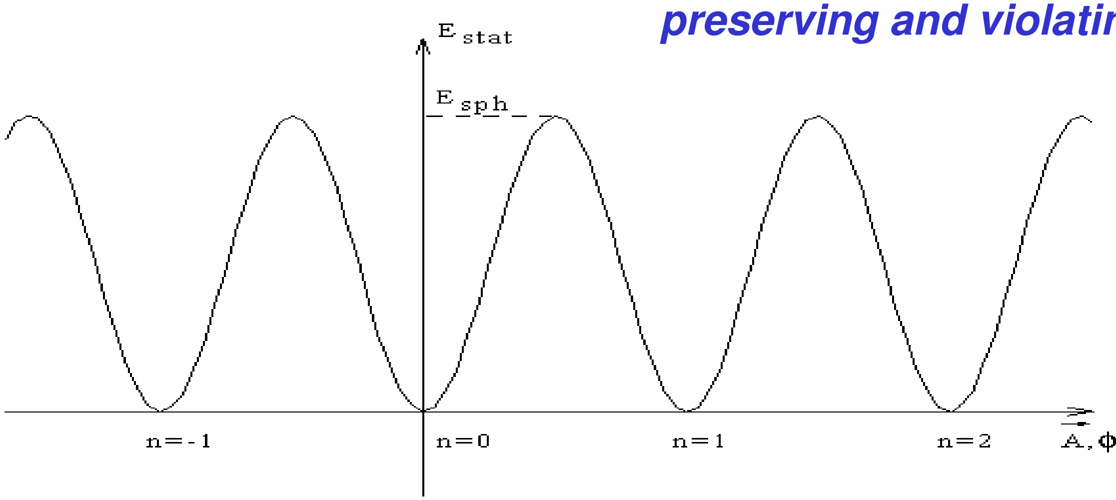
Non-equivalent Vacua and Static Energy in Field Configuration Space

Vacua carry different baryon number.
The sphaleron is a static configuration with non-vanishing values of the Higgs and gauge boson fields.

Its energy may be identified with the height of the barrier separating vacua with different baryon number

$$E_{sph} = \frac{8\pi \mathrm{v}}{g_W}$$

The quantity v is the Higgs vacuum expectation value, $\langle H \rangle = v$.
This quantity provides an order parameter which distinguishes the electroweak symmetry preserving and violating phases.



Baryon Number Violation at finite T

- Although at zero T baryon number violating processes highly suppressed
- At finite T, only Boltzman suppression

$$\Gamma(\Delta B \neq 0) \propto A T \exp\left(-\frac{E_{sph}}{T}\right)$$

- Baryon Number violating processes unsuppressed at high temperatures.
- Anomalous processes violate both baryon and lepton number, but preserve B – L. Relevant for the explanation of the Universe baryon asymmetry.

Generation of the

Matter - Antimatter

Asymmetry

Baryogenesis by Decay of Heavy Particles

- First simple models of baryogenesis proposed in the context of Grand Unified Models.

- A heavy GUT-scale particle *X* decays out-of-equilibrium with direct CP violation

$$B(X \to q) \neq B(\overline{X} \to \overline{q})$$

Heavy Particle Decay with $B - L \neq 0$

- Idea : Generate a non-vanishing lepton number at high energies.
- Baryon number generated from lepton number plus anomaly interactions, which convert L to B: Leptogenesis (Fukugita, Yanagida)
- Makes use of standard explanation of small neutrino masses.
- Relies in the presence of heavy Majorana neutrinos
- *Detailed calculation shows that lightest right handed neutrino mass should be* $M_M \sim 10^{10}$ GeV to obtain proper baryon asymmetry.

Neutrino Masses: Seesaw Mechanism

- Neutrino Masses much smaller than charged fermion ones
- Explanation: Neutrinos are Majorana particles. Dirac mass equal in size to charged particle masses.
- Large right handed mass. Mass matrix in base

$$(\nu_L, \nu_R) \qquad \begin{bmatrix} 0 & \mathrm{m_D} \\ \mathrm{m_D^T} & \mathrm{M} \end{bmatrix}$$

- Small mass eigenvalue, consistent with experiment if M is very large

$$\mathrm{m}_i = \frac{\mathrm{m}^2_{\mathrm{D_i}}}{\mathrm{M_i}} \qquad \left(\mathrm{m} = \mathrm{m_D}\,\mathrm{M}^{-1}\mathrm{m_D^T}\right)$$

Electroweak Baryogenesis

Baryogenesis at low Energies

(Kuzmin, Rubakov, Shaposhnikov)

- Idea : Baryon Number not generated at high energies, can be generated at the electroweak phase transition

Electroweak Baryogenesis

 - Start with $B = L = 0$
 - First-order phase transition . Rate suppressed in the broken phase: Non-equilibrium

$$\Gamma(\Delta \mathrm{B} \neq 0) \propto \mathrm{A\,T} \exp\left(-\frac{\mathrm{E_{sph}}}{\mathrm{T}}\right) \qquad E_{sph} = \frac{8\pi\, \mathrm{v}(\mathrm{T})}{g_W}$$

 - Creation of Baryon Number from CP violating sources

Electroweak Baryogenesis in the Standard Model

- SM fufills the Sakharov conditions:
- Baryon number violation: Anomalous Processes
- CP violation: Quark CKM mixing
- Non-equilibrium: Possible at the electroweak phase transition.

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s}\ \exp\left(-\frac{10^{16}}{\mathrm{T_c(GeV)}}\exp\left(-\frac{\mathrm{E_{sph}}(\mathrm{T_c})}{\mathrm{T_c}}\right)\right)$$

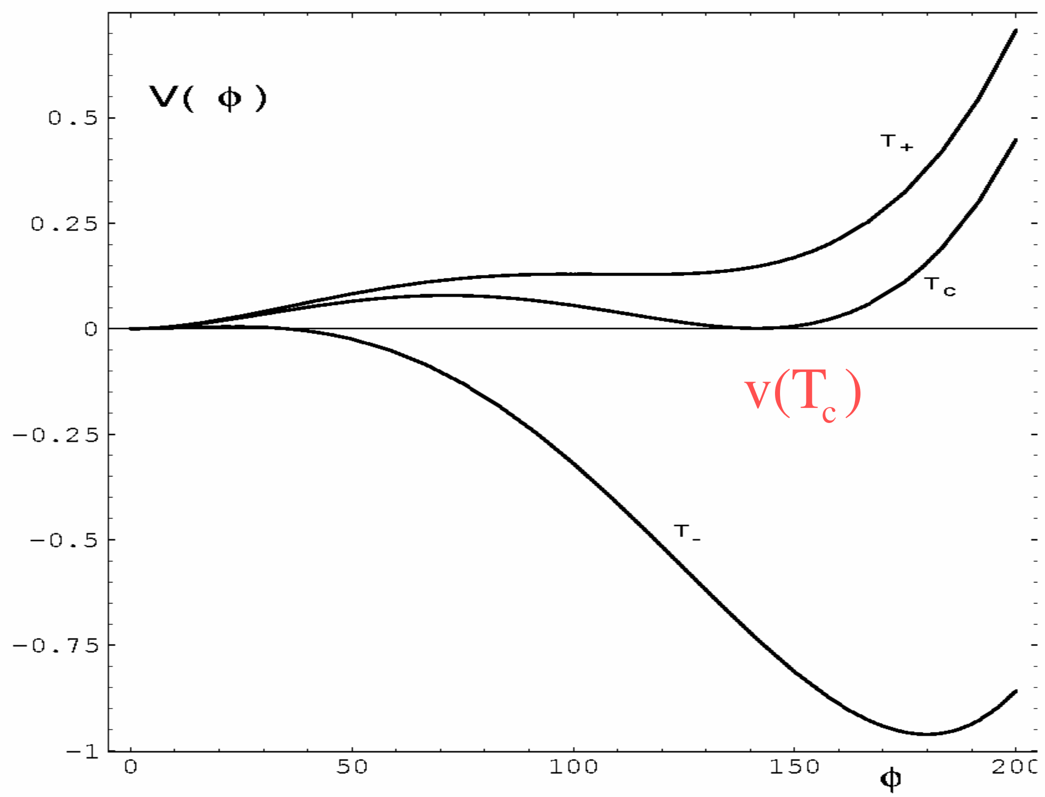
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry

$$\frac{\mathrm{v}(T_c)}{T_c} > 1$$

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order Phase Transition



Finite Temperature Higgs Potential

$$V = D(T^2 - T_0^2) H^2 + ET\ H^3 + \lambda\ H^4$$

While D receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration

E receives contributions proportional to the sum of the cube of all light boson particle couplings

$$\frac{\mathrm{v}(\mathrm{T_c})}{\mathrm{T_c}} \approx \frac{\mathrm{E}}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{\mathrm{m_H^2}}{\mathrm{v}^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass,

$$\frac{\mathrm{v}(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H \quad < 40 \text{ GeV}.$$

Electroweak Baryogenesis in the SM is ruled out

Problems in the Standard Model

- A more careful examination shows that, in the SM, phase transition is a cross over for any value of the Higgs mass.

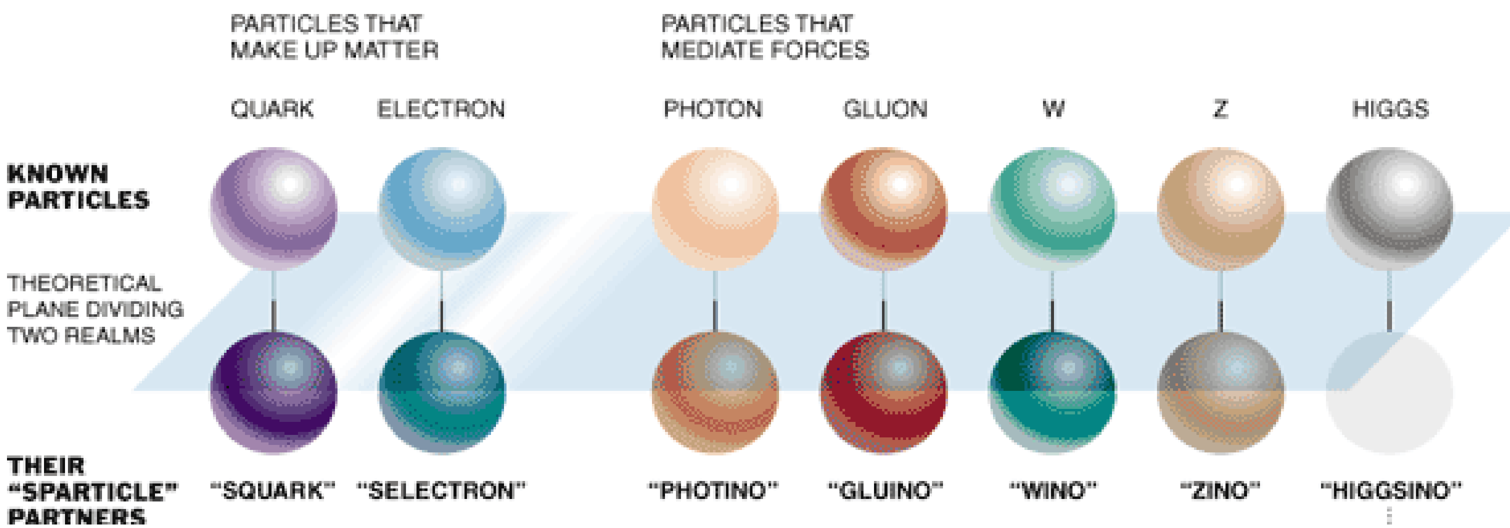
- Second, independent problem: Not enough CP violation. In the SM, this is measured by

$$\det[M_u^+ M_u, M_d^+ M_d] / T_c^{12} \approx 10^{-20}$$

- Both problems solved with Supersymmetry:
  Phase Transition strongly first order
  New CP violating phases

supersymmetry

fermions ⟷ **bosons**



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy

- Supersymmetry algebra contains the generator of space-time translations.
  Necessary ingredient of theory of quantum gravity.

- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.

- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Upper Bound on the Lightest Higgs Mass (minimal SUSY)

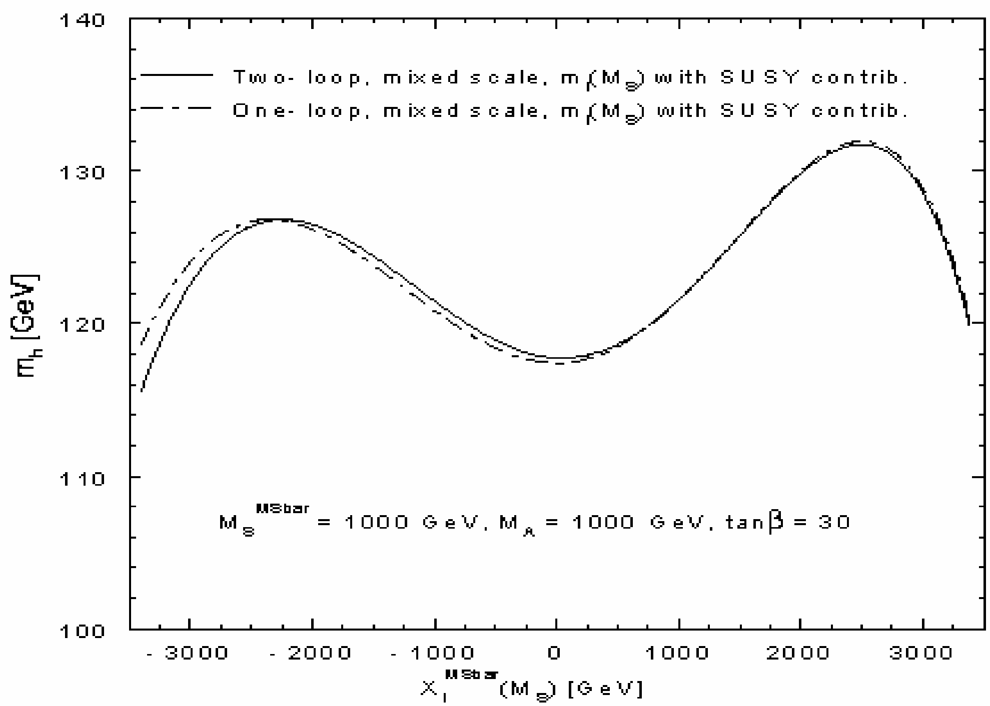
Supersymmetry requires two Higgs doublets. Two CP-even and one CP-odd neutral Higgs bosons.

$$< H_2 > = v_2 \quad , \quad < H_1 > = v_1$$

M_s= Mass of the top-quark superpartner

M_A = Mass of the heavy neutral Higgs bosons

X_t = Left-right Stop mixing parameter



Lightest Higgs boson mass smaller than 135 GeV.

M. Carena, M. Quiros, C.W. (1996); with Haber et al. (2000)

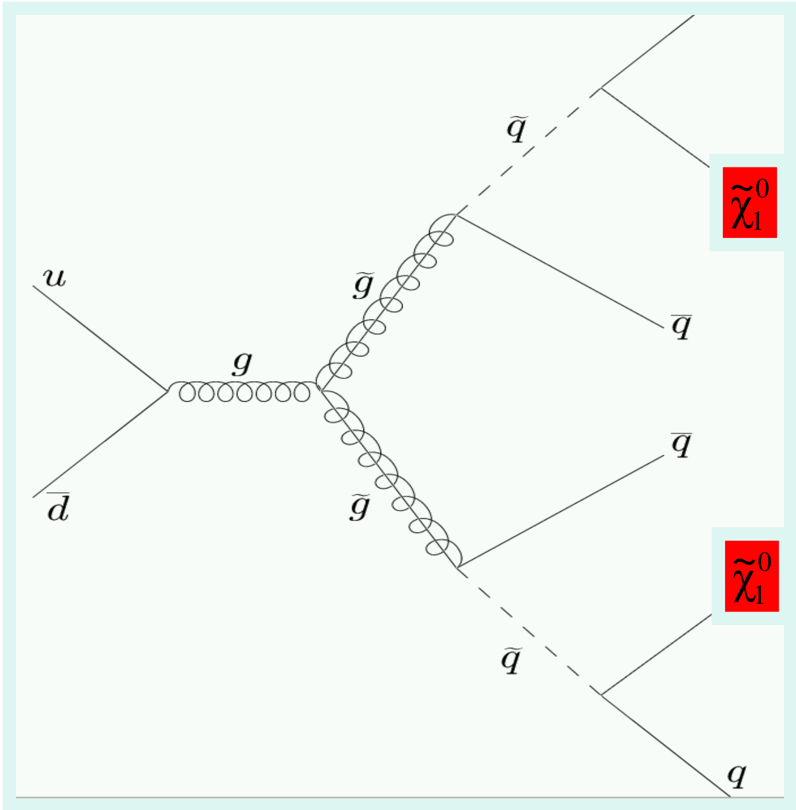
Supersymmetry at colliders

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Particles with large Yukawas tend to be lighter.

Charge-less particles tend to be the lightest ones.



- **Lightest supersymmetric particle = Excellent Cold dark matter candidate.**

Preservation of the Baryon Asymmetry

- EW Baryogenesis requires new boson degrees of freedom with strong couplings to the Higgs.

- Supersymmetry provides a natural framework for this scenario.

- Relevant SUSY particle: Superpartner of the top.

- Each stop has six degrees of freedom (3 of color, two of charge) and coupling of order one to the Higgs

$$E_{SUSY} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8\, E_{SM}$$

- Since $$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

Higgs masses up to 120 GeV may be accomodated

Constraints on the Stop Sector

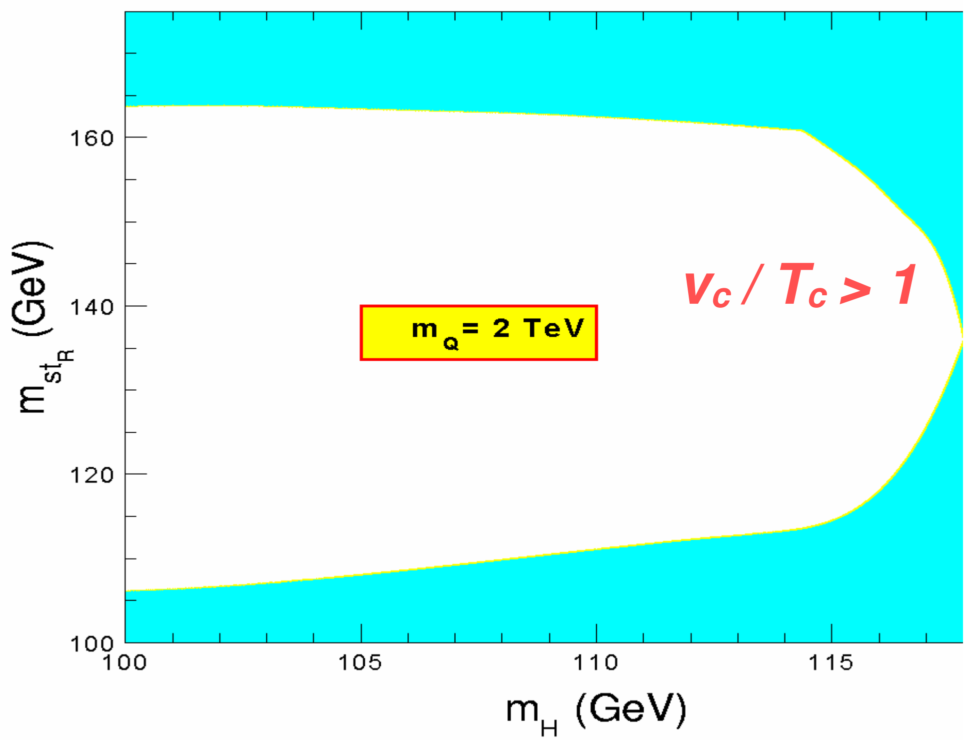
- The top quark has two supersymmetric partners, one for each chirality (left and right).

- One of the stops has to be light, in order to make the phase transitioin strongly first order

- Second stop needs to be heavier than about 1 TeV in order to make the Higgs mass larger than the current bound, of about 114 GeV.

- Upper bound on the Higgs imposed by the requirement of the preservation of the baryon asymmetry.

Limits on the Stop and Higgs Masses to preserve the baryon asymetry



Higgs masses smaller than 120 GeV and a stop masses below the top quark mass required

M.Carena, M. Quiros,C.W.' 98

Generation of the Baryon Asymmetry

- Superpartners of the Higgs and SU(2) gauge boson, with masses μ and M2 (charginos), play most relevant role.

- Baryon charge generated in walls of bubbles expanding at the time of the first order electroweak phase transition.

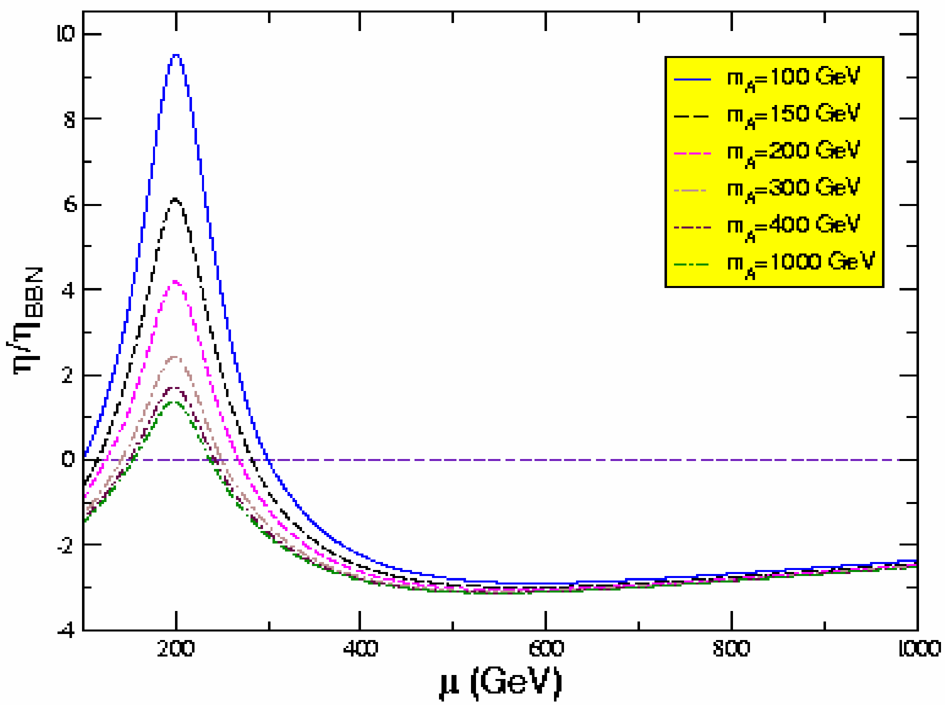
- CP-violating Sources depend on $\arg(\mu^* M_2)$
- also on the bubble wall Higgs profile.

- Higgs profile depends on the mass of the heavy Higgs bosons m_A.

Baryon Asymmetry Dependence on the Chargino Mass Parameters

$M_2 = 200$ GeV

Results for maximal CP violation



Gaugino and Higgsino masses of the order of the weak scale highly preferred

M.Carena, M.Quiros, M. Seco and C.W. '02

Baryon Asymmetry Enhanced for $M_2 = |\mu|$

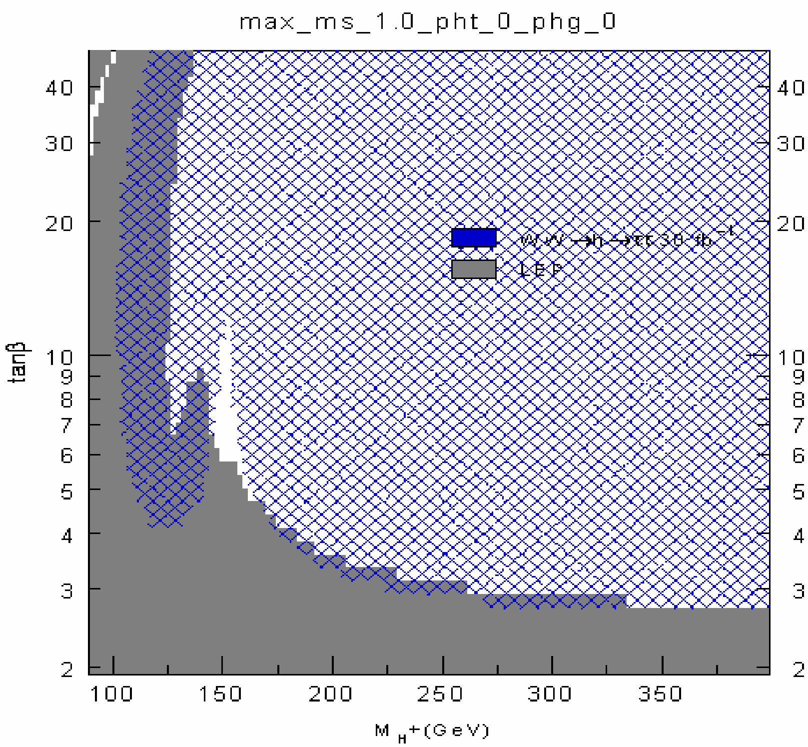
Even for large values of the CP-odd Higgs mass, acceptable values obtained for phases of order one.

Experimental Tests of Electroweak Baryogenesis

Higgs Searches

- Higgs with mass smaller than 120 GeV required
- Higgs associated with electroweak symmetry breaking: SM-like.
- Tevatron collider may test this possibility, if the luminosity is larger than about a few fb^{-1}
- A definitive test of this scenario will come with the LHC.

LHC Higgs Discovery Reach



W-fusion mode

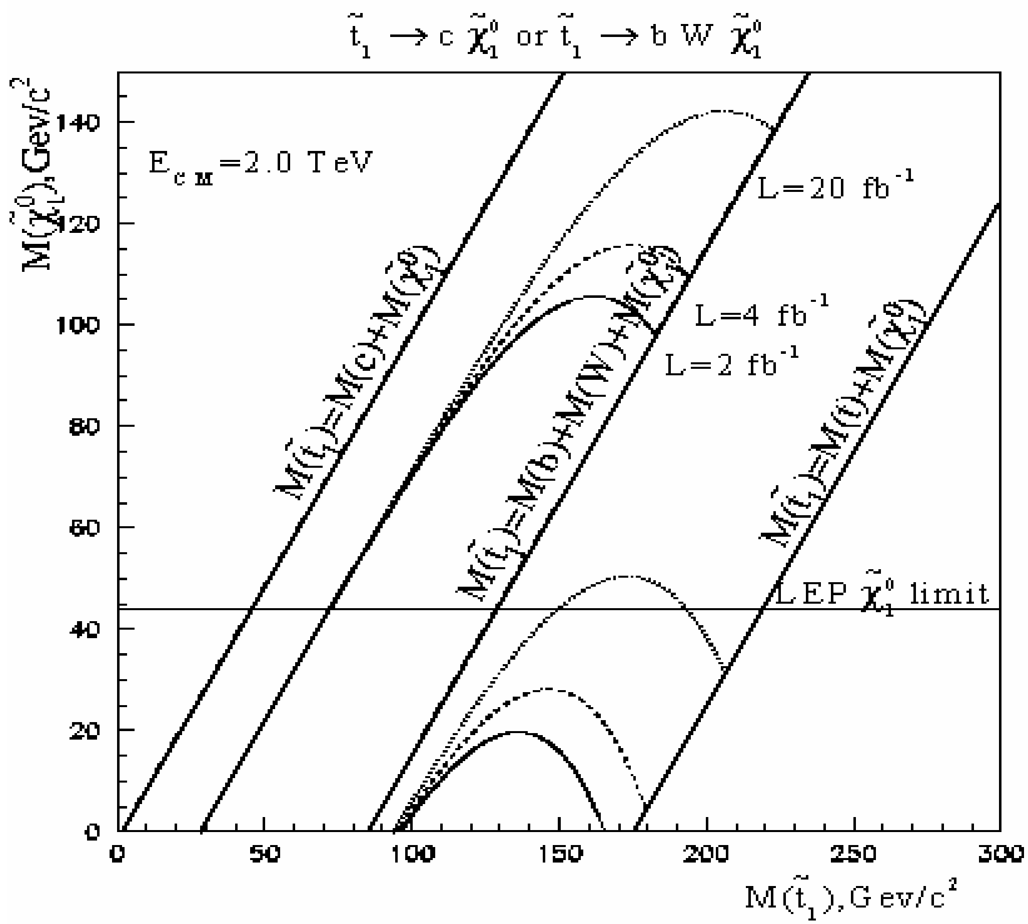
$$h \rightarrow \tau^+ \tau^-$$

After three years of low luminosity operation (30 inverse fb)

Stop Signatures

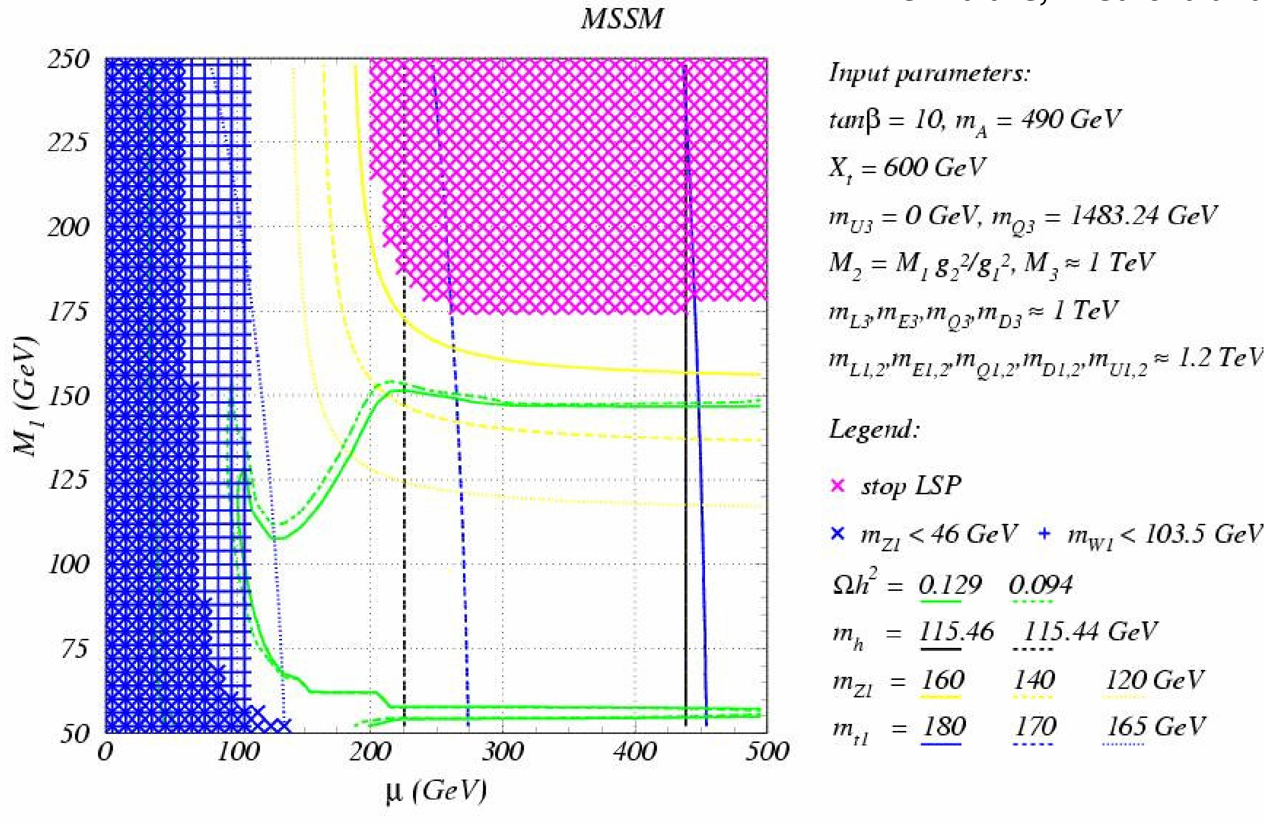
- Light Stop can decay into the lighter charginos or neutralinos.
- Stop signatures depend on this and also on the mechanism of supersymmetry breaking.
- In standard scenarios, where neutralino is the dark matter, stop may decay into a light up-quark and a neutralino: Two jets and missing energy.
- In models in which supersymmetry is broken at low energies, the neutralino may decay into a photon and a gravitino, the superpartner of the graviton.

Stop Signatures at the Tevatron
Neutralino as Dark Matter



Dark Matter and Electroweak Baryogenesis in the MSSM

C. Balazs, M.Carena and C.W. '04



Conclusions

- Supersymmetry may play a relevant role in the origin of particle masses, is consistent with unification and provides a dark matter candidate.

- It may also be essential in the generation of the baryon asymmetry if

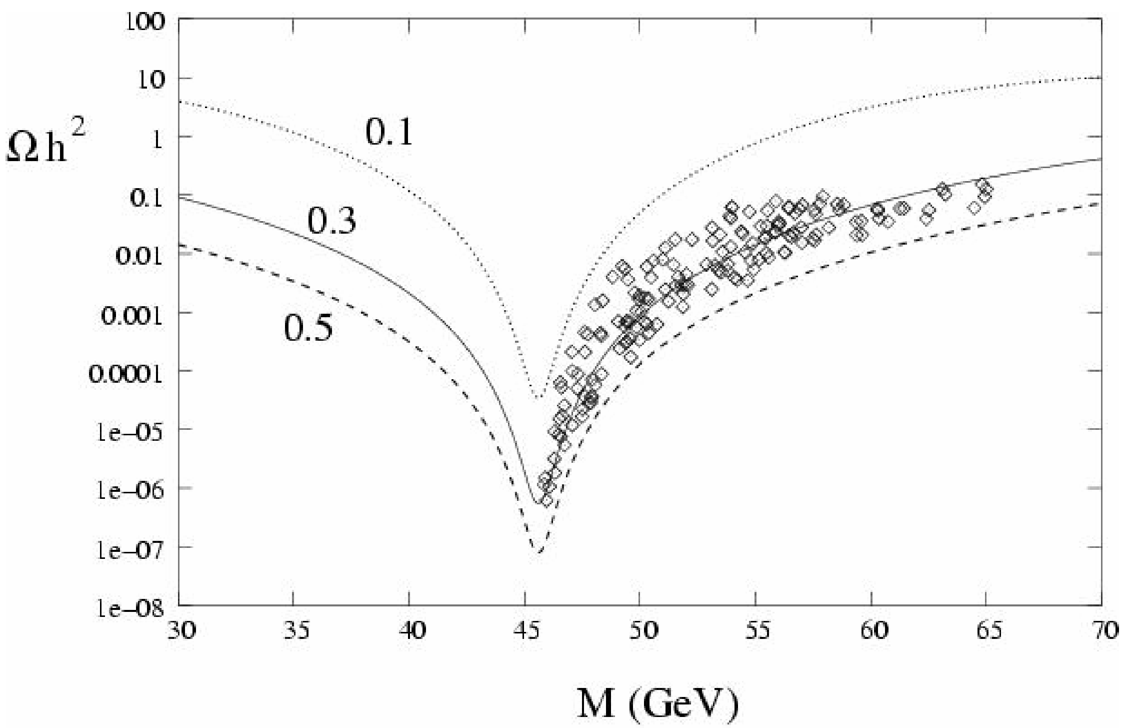
  $m_H < 120\ \mathrm{GeV}$ and $m_{stop} < m_{top}$

- Tevatron and LHC colliders will probe soon the realization of this scenario.

Additional Topics

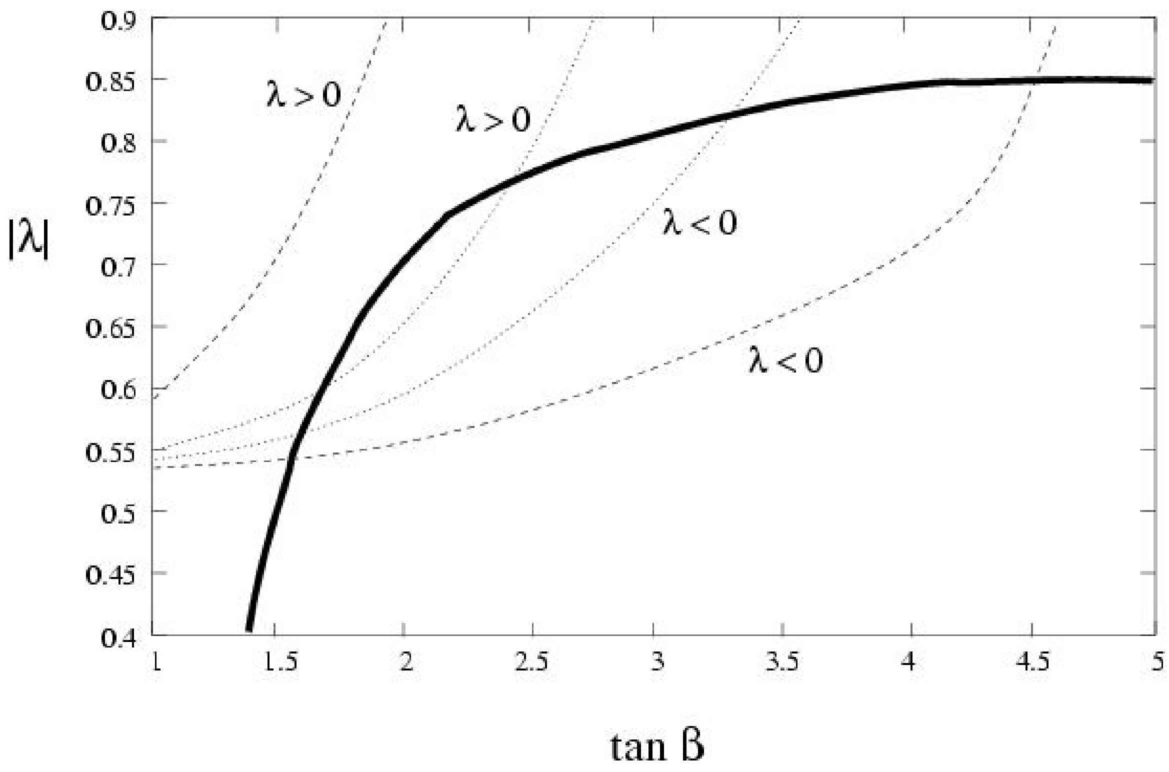
Dark Matter Density and Baryogenesis in the NMSSM

D. Morrissey, A. Menon and C.W. '04

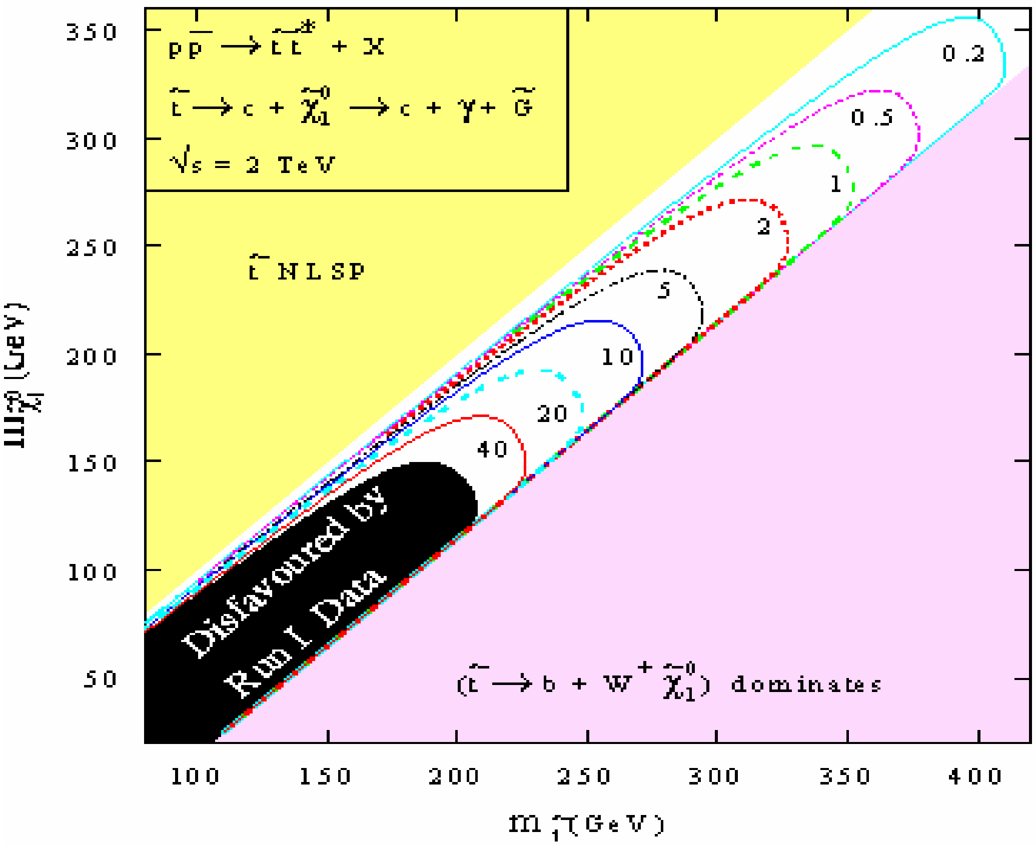


Baryogenesis and perturbativity limits

D. Morrissey,A.Menon and C.W. '04

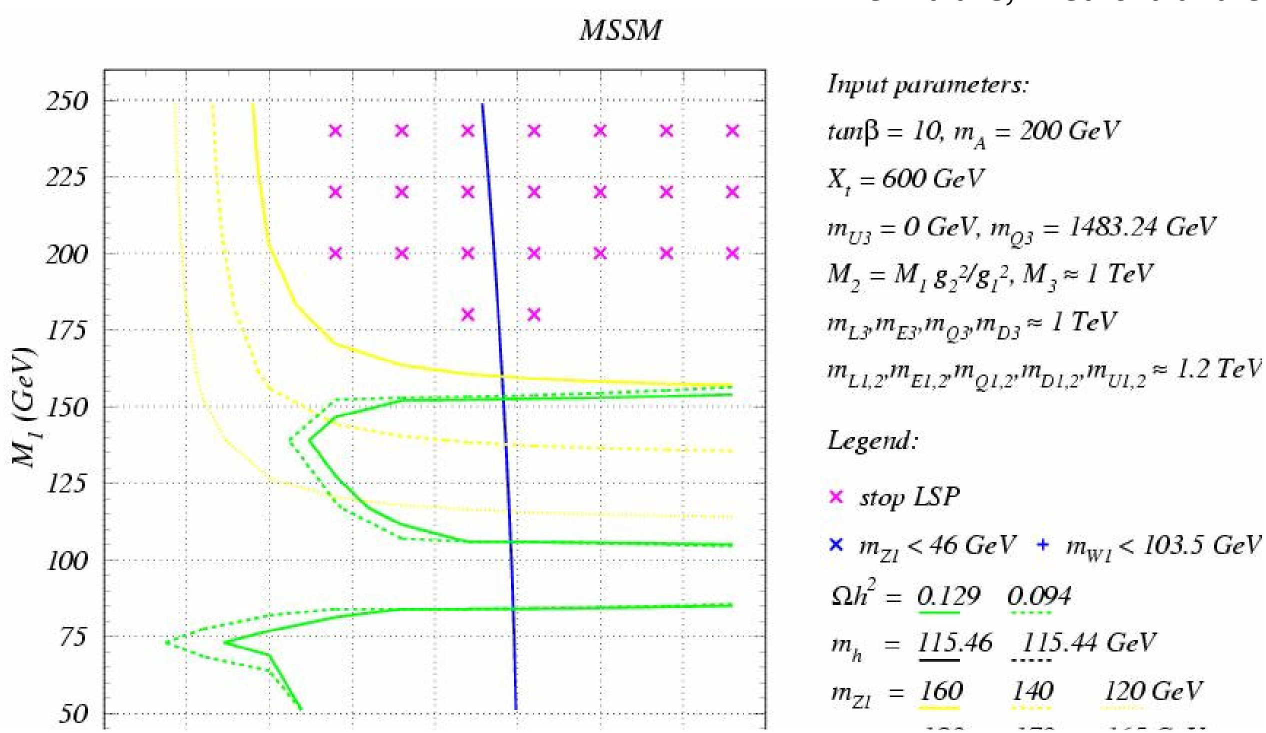


Stop Searches at the Tevatron
Neutralino decaying into photons



Electroweak Baryogenesis
and Dark Matter: small CP-odd Higgs mass

C. Balazs, M.Carena and C.W. '04



Anomalies arise in the process of regularization of divergences. Impossible to do it preserving gauge and B and L symmetries.

$$\partial^{\mu} j_{\mu}^{B,L} = \frac{N_g}{32\pi^2} Tr(\varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta})$$

Instantons are minimal action configuration with non-vanishing values of the integral of the right –hand side of the above Eq.

Instanton configurations may be regarded as semiclasical amplitudes for tunelling effect between vacuum states with different baryon number

$$S_{inst} = \frac{2\pi}{\alpha_W} \qquad \Gamma_{\Delta B \neq 0} \propto \exp(-S_{inst})$$

Weak interactions: Transition amplitude exponentially small. No observable baryon number violating effects at T = 0

Washout of Baryon Asymmetry

- *Baryon Number violated in the SM* at high temperatures.

- B-L, instead, is preserved by anomalous processes

$$\Delta B = \Delta L = N_g \quad \Rightarrow \quad \Delta(B\text{-}L) = 0$$

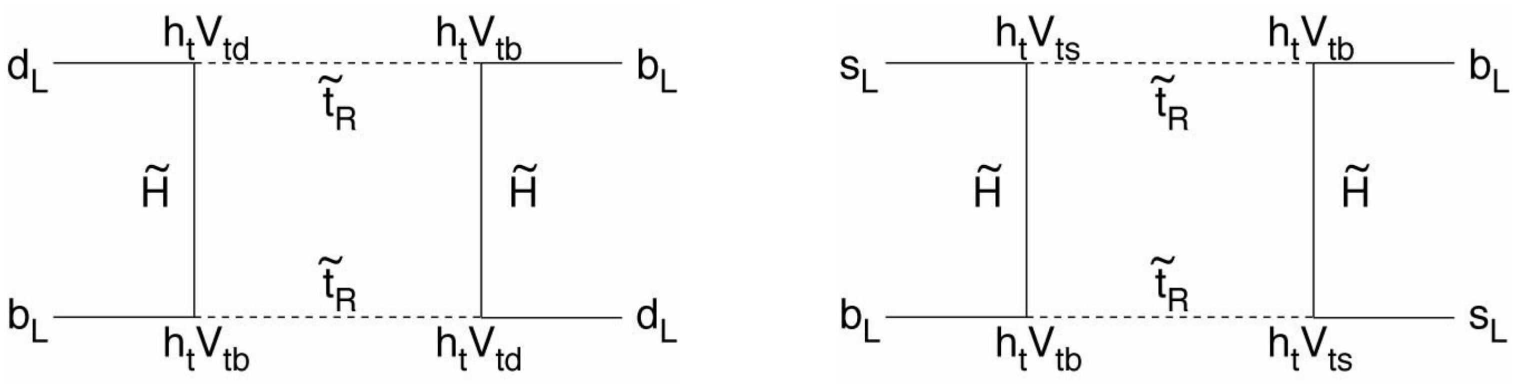
- If, original asymmetry had B = L, final asymmetry : B = L = 0.

- For successful generation of B asymmetry, decay of heavy particles should lead to

$$B - L \neq 0$$

Other Signals

– 20% enhancements to Δm_d, Δm_s with the same phase as in the SM (Murayama, Pierce)



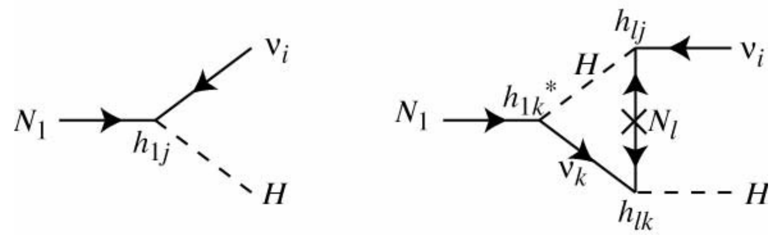
- Large phases in the chargino sector may induce large electric dipole moments for quarks and leptons: They lead to a bound on the first and second generation sfermions masses of about 2 TeV (Pilaftsis, Carena,Quiros,Seco and C.W.)

Generation Process

- Interaction with Higgs background creates a net chargino excess through CP-violating interactions
- Chargino interaction with plasma creates an excess of left-handed anti-baryons (right-handed baryons).
- Left-handed baryon asymmetry partially converted to lepton asymmetry via anomalous processes
- Remaining baryon asymmetry diffuses into broken phase
- Diffusion equations describing these processes derived

Leptogenesis

- Heavy, right-handed neutrinos decay out-of-equilibrium



- CP violating phases appear in the interference between the tree-level and one-loop amplitudes.

- Majorana fermions have extra physical phases. Two generations of neutrinos would be sufficient for the mechanism to work

- *Detailed calculation shows that lightest right handed neutrino mass should be* $M_1 \sim 10^{10}$ GeV to obtain proper baryon asymmetry.

- Leptogenesis may work even in the absence of supersymmetry. (In SUSY reheating temperatures of the order of dangerous, since they lead to overproduction of gravitinos).

Higgs Physics and Supersymmetry

- Quartic couplings of the Higgs boson governed by the gauge couplings.
- At tree level, the lightest Higgs boson mass is smaller than Mz (91 GeV).
- Prediction modified by radiative corrections induced by supersymmetry breaking effects.
- Most relevant particle : Superpartner of the top-quark (large coupling to the Higgs).

Relevant masses and Phases

- The chargino mass matrix contains new CP violating phases

$$\begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

- Some of the phases may be absorbed in field redefinition. For real Higgs v.e.v.'s, the phase

$$\arg(\mu^* M_2)$$

  is physical

- Sources depend on the Higgs profile. They vanish for large values of

$$\tan\beta = \frac{v_2}{v_1}$$